(54) Title: FLUID FLOW CONTROLLER AND METHOD OF OPERATION
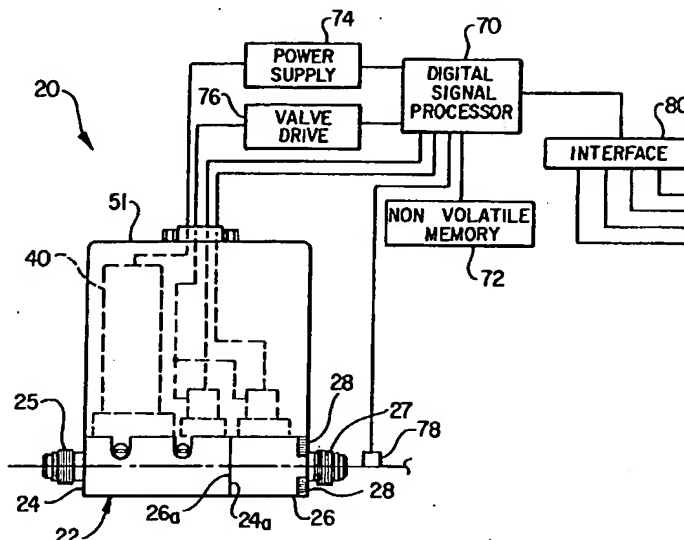
(57) Abstract: A fluid mass flow controller (20) includes a control circuit (70, 72, 74, 76, 80) connected to pressure sensors (46, 48) for sensing the differential pressure across a restrictor (56) for controlling a valve (40) to control the fluid mass flow rate to a setpoint. The control circuit (70, 72, 74, 76, 80) compares the differential pressure with the downstream pressure at a measured temperature with a data set of a gas passing through the flow controller (20) over a range of differential pressures and downstream pressures and adjusts the flow control rate accordingly. The flow controller (20) includes a two part body (22). The flow restrictor (56) may comprise an orifice or nozzle but preferably comprises a sintered metal plug having a predetermined porosity for the expected materials and flow conditions to which the flow controller (20) would be exposed.

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

FLUID FLOW CONTROLLER AND METHOD OF OPERATION

FIELD OF THE INVENTION

The present invention pertains to a fluid mass flow controller, particularly adapted for controlling the flow of toxic or highly reactive gases used in the fabrication of
5   semiconductor devices and the like and including a method of operation of the controller based on data which correlates controller operation with a fluid differential pressure across a flow restrictor part of the controller and the downstream fluid pressure viewed by the controller.

10   BACKGROUND

Some effort has been put forth to develop precision fluid mass flow controllers, particularly flow controllers for controlling the mass flow rates of fluids, such as toxic and highly reactive gases, of the type used in the
15   fabrication of semiconductor devices, for example. In the field of semiconductor fabrication, various gases are used in etching and vapor deposition processes, which gases are toxic to humans and are also highly reactive when exposed to ambient atmospheric conditions, for example. Mass flow
20   controllers have been developed which measure and control the flow rate of fluids of the above-mentioned type wherein the measurements are based on thermal properties of the fluids. Other fluid mass flow controllers have been developed which are based on measuring a pressure
25   differential across a flow restrictor or orifice. The accuracy of prior art fluid mass flow controllers of the

type in question here is inadequate for many applications of flow controllers.

Semiconductor fabrication processes may require the discharge of very precise quantities of fluids (primarily gases) into a process chamber. For example, flow rates ranging from as high as twenty liters per minute to as low as a few tenths of one cubic centimeter per minute (CCM) may be required. Moreover, the response time and stabilization rate of flow controllers used to control reactive gases in semiconductor fabrication may require that the controller be able to react to an "on" signal and be stable at the required fluid flow rate within 0.5 to 1.0 seconds. The process itself may last. anywhere from a few seconds to several hours and the shutoff response time of the fluid flow controller is usually required to be less than one second. The ability for thermal based fluid mass flow controllers to react and stabilize at such rates is difficult to achieve.

Another problem associated with prior art fluid mass flow controllers of the general type discussed herein pertains to the requirements to calibrate the controllers for various process fluids. Prior art fluid mass flow controllers are typically calibrated using an inert or nontoxic calibration fluid which requires the development of conversion factors or conversion data sets. Since the use of toxic or highly reactive process fluids for calibrating each controller instrument is cost prohibitive and dangerous to operating personnel, prior art mass flow controllers are typically calibrated on an inert fluid, such as nitrogen or argon, or a fluid whose properties are similar to the properties of the process fluid to be controlled by the mass flow controller. This process of using calibration fluids and conversion factors introduces errors into the operation

-2-

of the mass flow controllers, is time consuming and thus
expensive. The inaccuracy of prior art mass flow controllers
and the expense and time required to calibrate controllers
during initial setup, as well as in replacement procedures,
5   adds substantially to the cost of many manufacturing
processes, including the fabrication of semiconductor
devices, to the point that certain improvements in fluid
mass flow controllers have been highly desired.

Accordingly, several desiderata have been identified
10   for fluid mass flow controllers, particularly of the type
used in manufacturing processes as described above. Such
desiderata include controller accuracy within a few percent
of controller setpoint (at least one percent is desired),
operation at elevated or below "normal" temperatures and
15   various positions or attitudes (i.e., right side up,
sideways, or upside down), without loss of accuracy, such as
experienced by thermal based mass flow controllers, accurate
measurement and control over a wide range of flow rates,
fast response time from turn-on to achieving stable flow
20   conditions, economy of manufacture and uncomplicated modular
mechanical structure to facilitate servicing the flow
controller and to facilitate changing the flow controller
out of the fluid flow distribution system for the
manufacturing process. Other features desired in fluid mass
25   flow controllers include no requirement to calibrate each
complete controller instrument at the time of manufacture or
recalibrate the instrument after servicing, the provision of
a reliable easily interchanged flow restrictor or orifice
part, ease of verification of the operability and accuracy
30   of the flow controller after servicing or changeout of a
flow restrictor, the ability to accurately control flow
rates for a wide variety of toxic and/or reactive fluids,
particularly the hundreds of fluids in gaseous form which

-3-

are used in semiconductor fabrication processes, and ease of changing the controller working data for flow rates for different gases or fluids in liquid form. It is to these ends that the present invention has been developed.

5   SUMMARY OF THE INVENTION

The present invention provides an improved fluid mass flow controller and method of operation. In particular, an improved mass flow controller and method of operation are provided for use in connection with controlling the flow of

10 gaseous fluids' used in the manufacture of semiconductor devices and the like.

In accordance with one aspect of the present invention, a fluid mass flow controller is provided which utilizes measurements of differential pressure across a flow

15 restrictor and the pressure downstream of the flow restrictor to provide a more accurate reading of the actual mass flow of a particular fluid at a particular temperature. Such measurements may be carried out using only two pressure sensors or transducers and over a wide range of temperatures

20 of the fluid being measured.

The present invention further provides an improved fluid mass flow controller, particularly adapted for controlling the mass flow rate of toxic and reactive gases, including those used in the fabrication of semiconductor

25 devices wherein the flow controller includes rapid response time to stabilize at a desired setpoint flow rate and is accurate within setpoint conditions to less than one percent error. The controller is also operable to measure mass flow rates over a wide range of such flow rates, on the order of

30 a ratio of maximum to minimum flow rates as great as 100 to 1. The mass flow controller does not require calibration with a process fluid or with a calibration fluid and thus no

-4-

conversion factors are required in the flow measurement process.

The present invention also provides an improved fluid mass flow controller which operates by measurement of fluid differential pressures across and the fluid pressure downstream of a flow restrictor and which utilizes data for the mass flow of selected fluids within a range of differential pressures and downstream pressures to which the controller will be exposed and in which the controller will be operated. The mass flow controller and flowmeter of the invention is also operable over a wide range of inlet pressures from above atmospheric pressures to vacuum conditions experienced with so-called safe delivery systems for toxic or reactive gases. Still further, the invention includes a fluid mass flow controller which is operably associated with a control system including a suitable processor circuit, such as a digital signal processor, a nonvolatile memory for storing the aforementioned data and which may receive additional sets of data when desired.

The present invention further provides a fluid mass flow control apparatus which is of mechanically uncomplicated construction, is modular in form and is particularly adapted for rapid changeout of a replaceable flow restrictor, one or more pressure transducers and a single flow control valve associated with the controller.

The present invention still further provides a flow restrictor for which data of flow versus differential pressure and downstream pressure are available as data sets for a multiplicity of fluids, particularly adapted for use with a pressure based fluid mass flow controller or flowmeter in accordance with the invention, but is adaptable for other applications and is adapted for use with toxic and reactive gases, in particular.

-5-

Still further, the present invention contemplates a
method for measuring and/or controlling the mass flow rate
of a fluid by measuring differential pressures across a flow
restrictor and the fluid pressure downstream of the
5 restrictor, and particularly, but not limited to operating
conditions wherein the downstream pressure is below
atmospheric pressure. The invention further contemplates a
method of operation of a fluid mass flow controller which
does not require calibration of the controller with
10 calibration fluids but utilizes predetermined data sets for
a flow restrictor part of the controller for various types
of process fluids, including those which may be toxic or
highly reactive.

The invention also contemplates a fluid mass flow
15 controller including a microcontroller or processor device
adapted to receive signals from two pressure sensors, a
temperature sensor and command signal inputs while providing
a suitable analog output signal for a control valve
associated with the fluid mass flow controller. Still
20 further, the microcontroller is operable to support RS485
communication and various network communications for
receiving data from a remote site and for supporting and
inputting data to a serial EEPROM. Accordingly, the
invention contemplates a method of operation of a fluid mass
25 flow controller wherein data sets characterizing a flow
restrictor for different fluids may be obtained remotely via
a network for rapid change in operation of the controller on
various types of fluids.

Those skilled in the art will further appreciate the
30 above-mentioned advantages and superior features of the
invention together with other important aspects thereof upon
reading the detailed description which follows in
conjunction with the drawings.

-6-

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a somewhat schematic view of the fluid mass flow controller of the present invention;

FIGURE 2 is a longitudinal, generally central section view of the controller shown in FIGURE 1 and showing some features of fluid flow circuitry normally associated therewith;

FIGURE 3 is a detail section view of a flow restrictor used in the flow controller of FIGURES 1 and 2 and in accordance with the present invention;

FIGURE 4 is a diagram showing the mass flow rate of a gaseous fluid as a function of differential pressure across a flow restrictor and the downstream pressure, all in relatively low pressure ranges of about zero torr to about 2,000 torr;

FIGURE 5 is a longitudinal section view of another embodiment of the flow restrictor and an associated support fitting in accordance with the invention;

FIGURE 6 is a diagram similar to FIGURE 4 showing the characteristics of another type of flow restrictor as a function of differential pressure across and pressure downstream of the flow restrictor; and

FIGURES 7A and 7B are flow charts of certain steps carried out in the operation of the fluid mass flow controller shown in FIGURES 1 and 2.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

In the description which follows, like elements are marked through the specification and drawings with the same reference numerals, respectively. The drawings may not necessarily be to scale and certain features may be shown in generalized or schematic form in the interest of clarity and conciseness.

Referring to FIGURES 1 and 2, an improved fluid mass
flow controller in accordance with the invention is
illustrated and generally designated by the numeral 20. The
mass flow controller 20 includes a two-part modular body 22

5   comprising generally rectangular block shaped body parts 24
and 26 which may be suitably joined to each other by
conventional mechanical fasteners 28 at cooperating planar
faces 24a and 26a, respectively. The body parts 24 and 26
are provided with suitable fluid conductor connector portions

10 25 and 27 to provide for connecting the fluid mass flow
controller to conduits for a system for supplying, in
particular, toxic or reactive fluids in gaseous form for use
in semiconductor fabrication, for example.

By way of example, as shown in FIGURE 2, the mass flow

15 controller 20 may be interposed in a fabrication system
including a source pressure vessel 28 for pressure fluid such
as tungsten hexafluoride, chlorine, or sulfur hexafluoride,
for example. Source pressure vessel 28 is connected to the
flow controller 20 via a suitable conduit 30 and a purge

20 conduit 32 is also connected to conduit 30 and to a source of
purge gas, not shown, for purging the flow controller to a
suitable receiver or scrubber 34, when needed. During
operation of the flow controller 20, however, a precise flow
of fluid is controlled for entry into a semiconductor

25 fabrication chamber or vessel 36 via conduit 33. Chamber 36
is typically maintained at a substantially reduced pressure
by way of one or more vacuum pumps 37, for example. The
system in which the flow controller 20 is interposed, as
shown in FIGURE 2, is shown by way of example in simplified

30 form to illustrate one preferred application of the flow
controller.

Referring primarily to FIGURE 2, the body part 24
supports an electrically controlled flow control valve 40

-8-

which is removably mounted on a face 24b of body part 24 by conventional mechanical fasteners, not shown. Valve 40 includes an electrically actuated closure member 41 operable to throttle flow of fluid from an internal passage 42 of body

5　part 24 to a second internal passage 44 of body part 24. Valve 40 also includes an actuator 43 for the closure member 41. Actuator 43 is preferably of a type using a solenoid or piezoelectric material for rapid response and fineness of control of closure member 41. A first pressure transducer 46

10　is also removably mounted on body part 24 and is in communication with a passage 47 in body part 24 which is in communication with passage 44. A second pressure transducer 48 is removably mounted on body part 26 and is in communication with a passage 49 which opens into a

15　longitudinal passage 50 in body part 26, which passage is also connected to conduit 33 leading to the fabrication chamber 36. Pressure transducers 46 and 48 may be of a type commercially available from Honeywell Data Instruments Division, for example. Control valve 40 and pressure

20　transducers 46 and 48 may be disposed within a removable cover 51, FIGURE 1, for the flow controller 20.

　　　　Referring also to FIGURE 3, the body part 24 includes a cylindrical counterbore 54 formed therein and concentric with the passage 44 for receiving a flow restrictor 56. Flow

25　restrictor 56 is supported in a tubular sleeve 58 which may be mounted in a suitable tubular adapter 60 supported in the counterbore 54 between seal rings 62. Accordingly, the flow restrictor 56 may be easily removed from the body 22 by separating the body parts 24 and 26, removing the flow

30　restrictor together with its support sleeve 58 and replacing the flow restrictor with a suitable replacement restrictor of the same flow characteristics or a selected other flow characteristic. The flow restrictor 56 preferably comprises a

-9-

sintered metal cylindrical plug shaped member having a predetermined porosity for allowing fluid to flow therethrough by providing restriction to flow sufficient to create a differential pressure thereacross which may be
5 sensed by the pressure transducers 46 and 48. Flow restrictor 56 may, for example, be fabricated of stainless steel or nickel particles suitably compressed and sintered to provide the desired porosity and flow restriction characteristic. Flow restrictor 56 is advantageously disposed in flow
10 controller 20 downstream of control valve 40.

Referring again to FIGURE 1, the flow controller 20 is adapted to be operated by a control circuit or system including a microcontroller characterized as a digital signal processor 70 which is operably connected to a non-volatile
15 memory, such as an EEPROM 72, a power supply 74 and a suitable valve driver circuit 76. The microcontroller 70 is operably connected to the valve 40 for effecting movement of the closure member 41 by way of the driver 76. The microcontroller 70 is also operably connected to the pressure
20 transducers 46 and 48 and to a temperature sensor 78 which may be located to sense the temperature of fluid flowing through the controller 20 at a predetermined location. The microcontroller 70 is also operably connected to a suitable interface 80 for receiving command signals, data sets and
25 programming changes from various sources.

The microcontroller 70 is preferably a TMS320 LF2407 fixed point microcontroller available from Texas Instruments Incorporated. The pressure sensors 46 and 48 operate in a plus/minus 0.5 volt range with fourteen to sixteen bit
30 resolution as analog inputs to the microcontroller 70 which carries its own A/D and D/A converters. Other analog inputs will be for the temperature sensor 78 and a zero to five volt set point command signal input with twelve bit resolution.

-10-

The microcontroller 70 also provides analog output signals for controlling operation of the valve 40 via the driver 76. Communication with the microcontroller 70 may be via an RS485 4-wire communication link and/or a CAN (Controller Area Network). The microcontroller 70 is also capable of supporting a JTAG interface for emulation and debug and a powerup bootloader function for programming. The memory 72 is preferably a serial EEPROM of at least four thousand bytes.

The microcontroller 70 requires a closed loop control function to be executed at a rate of about one hundred times per second between the inputs for the pressure sensors 46 and 48 and the output signal for controlling the valve 40. Communication through interface 80 is carried out while the control loop is functioning although new data transfer or transfer to the memory 72 may be supplied when control loop updates are not being maintained.

An important aspect of the present invention resides in the discovery that, in a normal operating range of the mass flow controller 20, the fluid flow rate is a function not only of the differential pressure across the flow restrictor 56 but also the absolute downstream pressure corresponding substantially to the pressure in the fabrication chamber 36. FIGURE 4, for example, shows a typical characteristic of flow in standard cubic centimeters per minute (SCCM) as a function of the differential pressure (torr) across the flow restrictor 56 and also as a function of the downstream pressure (torr) in the passage 50, conduit 33 and fabrication chamber 36. The diagram of FIGURE 4 indicates that the flow characteristics of a fluid flowing across a restrictor, in the pressure ranges indicated in the diagram, may be in accordance with a three-dimensional surface indicated by numeral 90. The flow characteristic or surface 90 is for a

particular temperature. In the diagram of FIGURE 4, the mass flow characteristic 90 for the fluid tested was conducted at 25°C. As indicated in FIGURE 4, measurements taken at lower temperatures would provide flow characteristics indicated by

5   the surfaces 92 and 94, for example. The flow characteristic indicated by surface 92 is for a temperature lower than the temperature for the flow characteristic indicated by surface 90 and the flow characteristic which is determined by the surface 94 is at a temperature lower than the measurements

10 taken for developing the flow characteristic surface 92.

It will also be noted from viewing FIGURE 4 that a mass flow rate across a flow restrictor, particularly for the pressure ranges indicated in the diagram, varies with the downstream pressure. For example, if the downstream pressure

15 is approximately 0.0 torr and the pressure differential across the flow restrictor is approximately 1575.0 torr, the flow rate for the particular restrictor tested is about 280 SCCM. However, if the downstream pressure is 760.0 torr (standard atmospheric pressure), the flow rate for the same

20 pressure differential across the flow restrictor is approximately 500 SCCM. Accordingly, the behavior of fluids flowing across a flow restrictor, particularly in gaseous form, is dependent not only on temperature and differential pressure but also the pressure downstream of the flow

25 restrictor.

The flow characteristics indicated in FIGURE 4 at various temperatures, differential pressures across the flow restrictor and downstream pressures are for a sintered metal type flow restrictor, such as the flow restrictor 56.

30 Alternatively, viewing FIGURE 6, a similar flow characteristic is indicated for a sharp edged circular orifice at 25°C and is indicated by numeral 95. The specific flow characteristics shown in FIGURES 4 and 6 are for

nitrogen gas although other gases are indicated to behave in accordance with the general flow characteristics shown in FIGURES 4 and 6 for the types of flow restrictors described herein.

5   Accordingly, a flow characteristic in accordance with the diagrams of FIGURES 4 and 6 may be developed for particular types of flow restrictors used in connection with a mass flow controller, such as the controller 20, and for various fluids in liquid and gaseous form, including the
10   process gases or vapors used in semiconductor fabrication.

Data points representing the three-dimensional flow characteristics, such as the surfaces 90, 92 and 94 in FIGURE 4, may be developed in various ways and entered into the memory 72 of the flow controller 20. The flow controller
15   microcontroller 70, when operated in a set point mode can be programmed to command operation of the valve 40 to adjust the flow through the flow controller 20 to approach the setpoint by sensing the pressure differential across the flow restrictor by the pressure transducers 46 and 48 to determine
20   the actual flow rate, repeatedly, until the flow rate is essentially that programmed into the microcontroller 70 as the setpoint or pursuant to instructions input to the microcontroller. The data points representing the surfaces 90, 92 94 for a particular gas may be obtained using
25   conventional flow measuring equipment.

A rate of change mass flow measuring apparatus may also be used to obtain the data points. Moreover, such a flow measuring apparatus may be used to verify the operation of a flow controller, such as the flow controller 20 within its
30   design specification, and such apparatus may also be used to verify whether or not a particular flow restrictor is within its design specification. Once a design specification has been established for a flow restrictor and a flow controller

-13-

of the types described herein, the performance of each may be verified by a rate of change mass flow measuring apparatus or other mass flow measuring apparatus or devices and use of an inert gas so that toxic and highly reactive gases are not

5   required to be used during verification tests on the complete flow controller or on a flow restrictor, respectively. For example, a selected number of data points may be verified at flow rates of 50, 100, 500 and 3,000 SCCM at 30 psig inlet pressure, with exhaust pressure being atmospheric, for a flow

10 controller, such as the controller 20, or for a flow restrictor, such as flow restrictor 56. Data points representing the design specification of the flow controller 20 may also be entered into the memory 72 to verify the operability of the flow controller when tested with the

15 aforementioned rate of change flow measuring apparatus. A suitable rate of change or so-called rate of rise mass flow measuring apparatus is commercially available.

Moreover, the fluid mass flow controller 20 may also be connected via its interface 80 with a network adapted to be

20 connected to a source of data for any fluid which has been tested in conjunction with a controller of the same type as the flow controller 20. In this way, any gas to be controlled by the flow controller 20 may have its flow characteristics entered into the memory 72 by merely querying a database

25 stored in a suitable processor. For example, a vendor of the flow controller 20 may have selected data sets stored on a suitable processor and memory associated therewith for a wide variety of gases, each data set corresponding substantially to the type of data sets that would provide the flow

30 characteristics shown in FIGURES 4 and 6 for any one type of flow restrictor, respectively. An authorized customer using a flow controller, such as the flow controller 20, and desiring to begin using the controller with a particular gas would

-14-

merely make an inquiry to the vendor source and download the needed data set directly to the microcontroller 70 and its memory 72 via a network such as the Internet, for example.

Operation of the microcontroller 70 is generally in accordance with the flow diagrams of FIGURES 7A and 7B and will now be described in further detail. The microcontroller or processor 70 is operable to execute closed loop control and communication functions. Closed loop control is preferably executed at a rate of 100 times per second and requires execution of lookup tables or polynomial calculations. All code may be written in "C". The functions of the microcontroller or processor 70 are summarized in the flow diagram of FIGURE 7A. Step 100 in FIGURE 7A indicates a 10 millisecond interrupt to drive the key functions of the processor 70. In step 102, the processor obtains 64 samples of downstream pressure XD1 and averages the samples. In step 104, the processor 70 obtains 64 samples of the upstream pressure XD2 and averages the samples. Step 106 is an averaging of 32 samples of an analog output signal for control of the valve 40 identified by the software tag CV1SN. Step 108 indicates operation of the processor 70 in the signal mode to obtain 32 samples of a zero to five volt setpoint command signal input in step 110, and a 32 sample zero to five volt analog output signal in step 112. Step 114 indicates when analog inputs are shorted to ground. Step 116 indicates the processor obtaining 32 samples of the signal from temperature sensor 78, indicated as TE1, and averaging such samples. Step 118 provides for converting the signal inputs to English units of pressure, flow and temperature. Step 120 in FIGURE 7A is the execution of a calculation of flow routine using, for example, the surfaces 90, 92 and 94 of FIGURE 4. New processor proceeds to the control mode at step 122.

FIGURE 7B illustrates how the calculation of flow routine is carried out using sets of so-called three dimensional maps, such as the surfaces 90, 92 and 94, for example, for respective operating temperatures and whereby

5   the flow is calculated as a function of the variables of differential pressure across the flow restrictor 56, the downstream pressure in the flow passage 50 and the temperature sensed by the sensor 78. A set of flow runs over a range of downstream pressures and flow rates is obtained

10   for the flow restrictor 56. This data set is fitted to an array of three dimensional curves. The so-called map can be thought of as flow on the z axis mapped to differential pressure, XD2-XD1, on the x axis and discharge or downstream pressure, XD1 on the y axis.

15   The best-fit process generates curves at various values of y. Typically curves of x versus z might be generated for XD1 being equal to 1, 50, 100, 300, 500 and 700 torr, for example. Then the process is repeated at another operating temperature. The calibration data is then mapped from

20   floating point numbers to the fixed point quantities that are used in the processor. These tables are download to the processor and are called during the flow calculations. The get calibration data of step 124, FIGURE 7B, is carried out by obtaining the calibration maps or surfaces at the nearest

25   temperature above and below the temperature sensed by sensor 78. At steps 126 and 128, flow is calculated by interpolating the differential pressure XD2-XD1 for two curves in the calibration data (CAL DATA). Flow at the current calibration temperature is calculated by interpolating between

30   calibration flow data points. At steps 130 and 132 flow at the current CAL DATA temperature is calculated by interpolating between Flow(0) and Flow(i) by the value of XD1 and the y axis values for Flow(0) and Flow(1). Flow is

calculated by interpolating between the Flow@Temp(0) and Flow@Temp(1) by the value of TE1 and the temperatures for the two CAL DATA sets selected.

Referring briefly to FIGURE 5, as previously mentioned
5   the flow restrictor 56 may be adapted for operation in conjunction with other flow controllers and related devices. The flow restrictor 56 may, for example, be removably mounted in a conventional fitting, such as a face seal union fitting 110. The fitting 110 includes a longitudinal through passage
10   112 which is counterbored at one end to provide a bore 114 for receiving the cylindrical plug flow restrictor 56 and its tubular support sleeve 58. The sleeve 58 may be a light press fit in the bore 114. By way of example, a flow restrictor for use in conjunction with the flow controller 20 may be
15   characterized as a cylindrical plug having a diameter of approximately 0.18 inches and a length of approximately 0.18 inches and may be formed of porous sintered stainless steel, nickel or Hastelloy C-22. The solid steel sleeve 58 may be formed of 316L stainless steel. It is contemplated that the
20   manufacturing tolerances of the flow restrictor 56 may be such as to require only verification of the performance characteristics of the restrictor by verifying the mass flow rates of, for example, 50, 100, 500 and 3,000 SCCM at a pressure upstream of the restrictor of 30 psig with exhaust
25   to atmosphere.

Accordingly, no calibration or calibration conversion factors are necessary for the flow restrictor 56 or the flow controller 20. When once placed in use, the flow controller 20 and/or the flow restrictor 56 may be verified as to its
30   operability by flowing predetermined quantities of an inert gas through these devices using the aforementioned rate of change flow measuring apparatus or a similar apparatus to verify performance. The flow restrictor and/or the flow

-17-

controller may then be placed in or returned to service with assurance that the respective devices will perform in accordance with a flow characteristic, such as that indicated in FIGURE 4, for example.

5   The construction and operation of the mass flow controller 20 and the flow restrictor 56, as well as the method of operation of the flow controller as set forth hereinabove, is believed to be readily understandable to those of ordinary skill in the art. Moreover, the flow
10   controller 20 functions as a flowmeter and may be used as a flowmeter as well as for controlling fluid flow rate to a setpoint condition.

Although preferred embodiments of the invention have been described in detail herein, those skilled in the art
15   will recognize that various substitutions and modifications may be made to the invention without departing from the scope and spirit of the appended claims.

WHAT IS CLAIMED IS:

1.   A fluid mass flow controller for controlling flow
of fluid to a process, said mass flow controller comprising:
a body including a fluid flow passage therein;
a flow restrictor interposed in said flow passage
5 in said body;
a pressure sensor for sensing the fluid pressure
in said flow passage upstream of said flow restrictor and a
pressure sensor for sensing the fluid pressure in said flow
passage downstream of said flow restrictor;
10   a control valve for controlling the flow of fluid
through said flow passage; and
a control circuit operably connected to said
control valve and to said pressure sensors for controlling
the mass flow of fluid through said flow controller based on
15 sensing a differential pressure across said flow restrictor
and fluid pressure in said flow passage downstream of said
flow restrictor.

2.   The mass flow controller set forth in Claim 1
wherein:

        said control circuit includes a microcontroller
operably connected to said pressure sensors and said flow
5   control valve and to a memory including data specifying the
mass flow rate through said flow restrictor for said fluid
and for a differential pressure across said flow restrictor
and a pressure of fluid flowing through said flow restrictor
and downstream of said flow restrictor, said microcontroller
10   being operable to provide one of an output signal indicating
a flow rate of said fluid through said flow controller at a
particular condition of pressure differential, downstream
pressure and temperature and operating said control valve to
limit the flow of said fluid through said flow controller to
15   a predetermined amount based on a set point fluid flow rate
communicated to said microcontroller.

3.   The mass flow controller set forth in Claim 2
including:

        an interface connected to said microcontroller and
operable to be connected to a source for receiving a data
5   set of fluid mass flow rates versus differential pressures
across said flow restrictor and the pressures downstream of
said flow restrictor in said flow controller for at least
one predetermined fluid composition.

4.   The mass flow controller set forth in Claim 2
wherein:

said microcontroller includes a data set for a
verification fluid residing in said memory for verifying
5   flow control rates of verification fluid at predetermined
temperatures, differential fluid pressures across said flow
restrictor and fluid pressures downstream of said flow
restrictor.

5.   The mass flow controller set forth in Claim 1
wherein:

said flow restrictor comprises a porous plug.

6.   The mass flow controller set forth in Claim 5
wherein:

said flow restrictor comprises a sintered metal
plug having a predetermined porosity.

7.   The mass flow controller set forth in Claim 6
wherein:

the porosity of said flow restrictor corresponds
to plural predetermined mass flow rates of a predetermined
5   fluid at a predetermined upstream pressure and a predeter-
mined downstream pressure with respect to said flow
restrictor.

8. The mass flow controller set forth in Claim 1 wherein:

said body comprises a first body part and a second body part releasably connectable to said first body part at cooperating faces of said first body part and said second body part and said flow restrictor is mounted in one of said body parts in a counterbore formed therein and is removable therefrom upon separation of said body parts from each other.

9. The mass flow controller set forth in Claim 8 wherein:

one of said pressure sensors is mounted on said first body part and the other of said pressure sensors is mounted on said second body part, each of said pressure sensor being in communication with a passage intersecting said flow passage in said body.

10. The mass flow controller set forth in Claim 9 wherein:

said control valve is mounted on said first body part and includes a closure member interposed in said flow passage.

11. The mass flow controller set forth in Claim 1 wherein:

said control circuit includes a microcontroller comprising a digital signal processor, a memory connected to said digital signal processor, a valve driver circuit interposed said control valve and said microcontroller and an interface for connection to one or more networks for communicating at least one of data and commands to said microcontroller.

12.   The mass flow controller set forth in Claim 11
wherein:

said memory includes a data set representing the
mass flow rate of a specified fluid over a range of
5   differential pressures across said flow restrictor and a
range of pressures in said flow passage downstream of said
flow restrictor for a given temperature.

13.   The mass flow controller set forth in Claim 12
including:

plural data sets in said memory for predetermined
fluid mass flow rates based on pressure differentials across
5   a flow restrictor and the pressure of said fluid downstream
of said flow restrictor for a plurality of temperatures of
said fluid flowing through said mass flow controller.

14.   The mass flow controller set forth in Claim 12
including:

plural data sets in said memory for predetermined
fluid mass flow rates based on pressure differentials across
5   a flow restrictor and the pressure of said fluid downstream
of said flow restrictor for a plurality of fluids of
different compositions, respectively.

15.   A fluid flowmeter for measuring the mass flow of a
known fluid composition, said flowmeter comprising:

a   body   including   a   fluid   flow   passage
therethrough;

5   a flow restrictor interposed in said flow passage
in said body;

a pressure sensor for sensing fluid pressure in
said flow passage upstream of said flow restrictor and a
pressure sensor for sensing fluid pressure in said flow
10   passage downstream of said flow restrictor; and

a   control   circuit   operably   connected   to   said
pressure sensors for measuring the mass flow of fluid
through said flowmeter based on sensing a differential fluid
pressure across said flow restrictor and fluid pressure in
15   said flow passage downstream of said flow restrictor.

16.   The flowmeter set forth in Claim 15 wherein:

said control circuit includes a microcontroller
comprising a signal processor, and a memory connected to
said signal processor, said memory including a data set
5   representing the mass flow rate of a specified fluid over a
range of differential pressures across said flow restrictor
and a range of pressures in said flow passage downstream of
said flow restrictor for a given temperature.

17.   The flowmeter set forth in Claim 16 including:

plural data sets in said memory for predetermined fluid mass flow rates based on pressure differentials across said flow restrictor and the pressure of said fluid

5   downstream of said flow restrictor for plural temperatures of said fluid flowing through said flowmeter.

18.   The flow meter set forth in Claim 16 including:

plural data sets in said memory for predetermined fluid mass flow rates based on pressure differentials across a flow restrictor and the pressure of said fluid downstream

5   of said flow restrictor for a plurality of fluids of different compositions, respectively.

19.   A flow restrictor for use in one of a flowmeter and a fluid mass flow controller for controlling relatively low flow rates of gaseous materials used in the fabrication of semiconductor devices, said flow restrictor being

5   characterized by a data set of at least one of said gaseous materials for a range of differential pressures across said flow restrictor and a range of fluid pressures downstream of said flow restrictor when said one gaseous material is flowed through a passage having said flow restrictor

10   interposed therein.

20.   The flow restrictor set forth in Claim 19 wherein:
said flow restrictor comprises a porous plug.

21.   The flow restrictor set forth in Claim 20 wherein:
said plug is formed of sintered metal.

-25-

22.   The flow restrictor set forth in Claim 20 wherein:

said flow restrictor is operable to provide plural predetermined mass flow rates of a verification gas flowed through said flow restrictor at a predetermined inlet
5   pressure upstream of said flow restrictor and a predetermined exhaust pressure downstream of said flow restrictor.

23.   A method for controlling the flow rate of a fluid to a process, comprising the steps of:

providing a fluid mass flow controller having a body, a flow passage through said body, a flow restrictor
5   interposed in said flow passage, a first pressure sensor for sensing fluid pressure upstream of said flow restrictor in said flow passage, a second pressure sensor for sensing pressure in said flow passage downstream of said flow restrictor and a control valve for controlling the flow of
10   fluid through said flow passage and said flow restrictor, said method comprising the steps of:

measuring the pressure of fluid flowing through said flow passage with said first and second pressure sensors;
15   determining the mass flow rate of fluid flowing through said controller based on the differential pressure across said flow restrictor and the pressure in said flow passage downstream of said flow restrictor; and

operating said control valve to vary the flow of
20   fluid through said flow passage until the mass flow rate of fluid flowing through said flow passage is substantially at a predetermined setpoint of mass flow rate of said fluid.

24. The method set forth in Claim 23 wherein:

said process is carried out at relatively low pressures in a range of about 760 torr to about 0 torr.

25. The method set forth in Claim 23 wherein:

the mass flow rate of fluid flowing through said flow passage is determined by comparing the pressure differential of fluid flowing across said flow restrictor and said downstream pressure in said flow passage with a data set of mass flow rates of the fluid being flowed through said flow passage to said process for various differential pressures across a flow restrictor and various pressures of said fluid downstream of said flow restrictor.

26. The method set forth in Claim 23 including the step of:

measuring the temperature of fluid flowing through said mass flow controller and comparing the differential pressure across said flow restrictor with the pressure in said flow passage downstream of said flow restrictor at said measured temperature.

27.   The method set forth in Claim 23 including the
steps of:

        obtaining data sets of flow rates of selected
fluids to be controlled by said controller by flowing said
5 selected fluids through said restrictor and measuring the
upstream and downstream pressures at multiple downstream
pressures.

28.   The method set forth in Claim 27 including the
step of:

        measuring the flow rates of said fluids using a
rate of change measurement apparatus.

29.   A method for measuring the mass flow rate of a
fluid, comprising the steps of:

        providing a body including a flow passage and a
flow restrictor interposed therein;
5   flowing said fluid through said flow passage and
measuring the pressures of fluid flowing through said flow
passage upstream and downstream of said flow restrictor; and

        comparing   the   pressure   differential   of   fluid
flowing   across   said   flow   restrictor   and   the   pressure
10 downstream of said flow restrictor with a data set of mass
flow rates of the fluid being flowed through said flow
passage for various differential pressures across said flow
restrictor and various pressures of said fluid downstream of
said flow restrictor.

30.   The method set forth in Claim 29 wherein:

        said pressures downstream of said flow restrictor
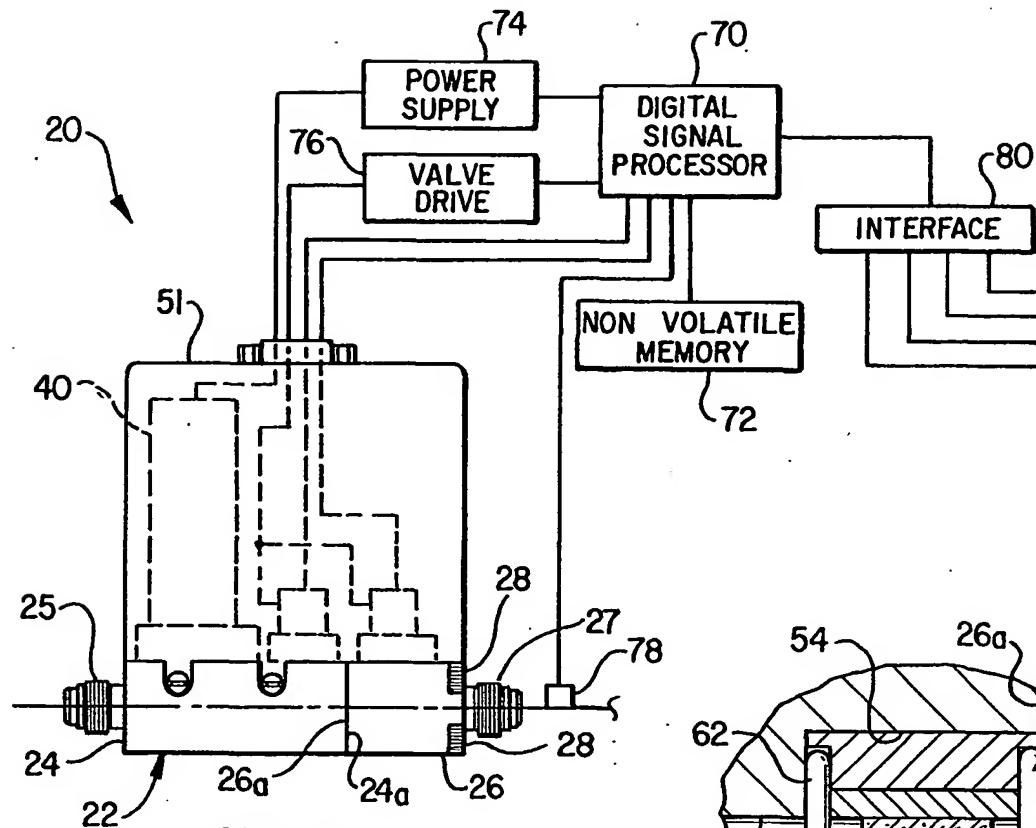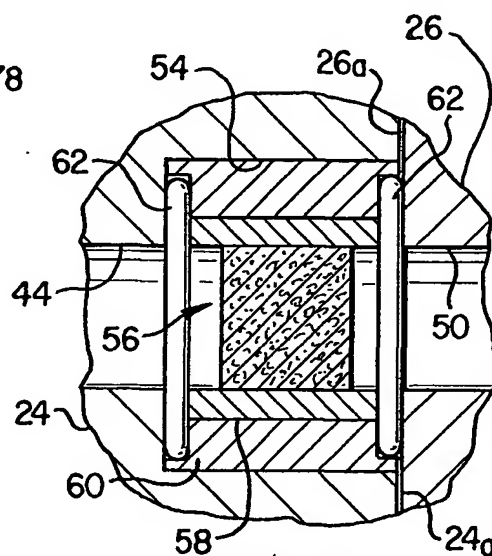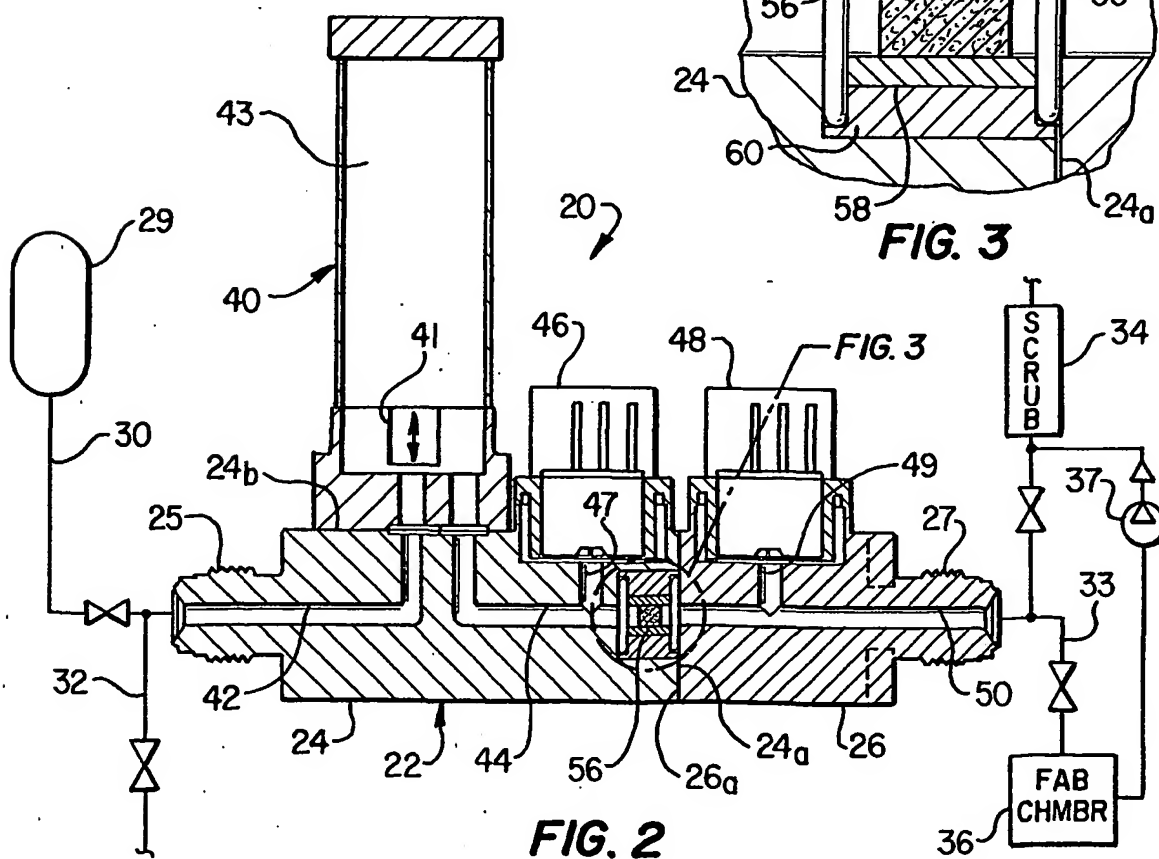are in a range of about 0 torr to 760 torr.

31.   The method set forth in Claim 29 including the
step of:

providing a fluid mass flowmeter including said
body, a first pressure sensor for sensing fluid pressure
5   upstream of said flow restrictor in said flow passage and a
second pressure sensor for sensing pressure in said flow
passage downstream of said flow restrictor.

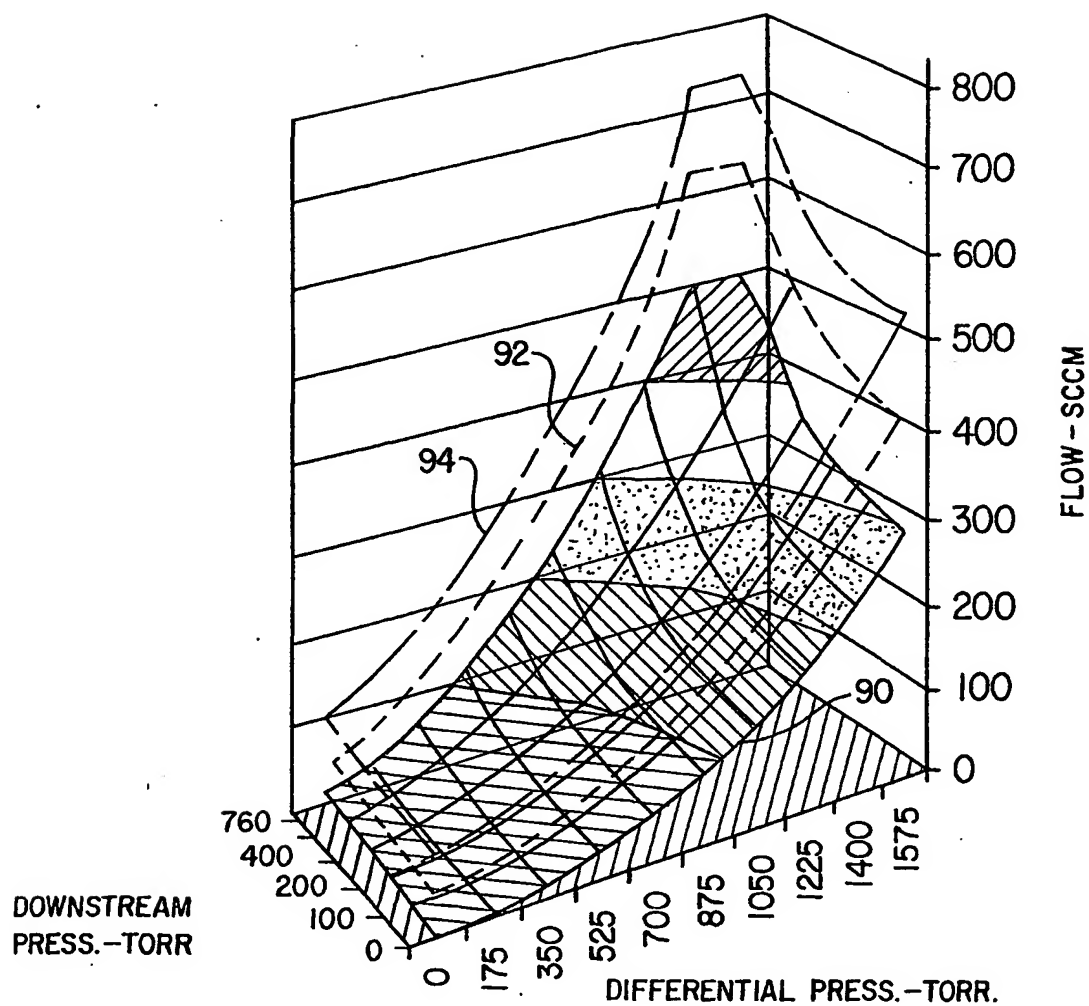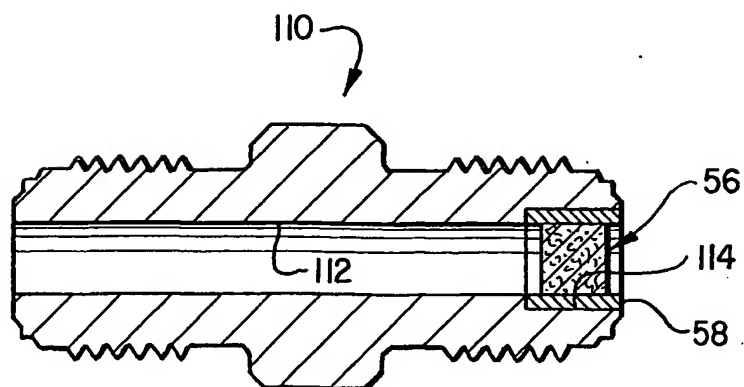32.   The method set forth in Claim 29 including the
step of:

measuring the temperature of fluid flowing through
said flow passage and comparing the differential pressure
5   across said flow restrictor and the pressure in said flow
passage downstream of said flow restrictor with a data set
of said mass flow rates for selected temperatures above and
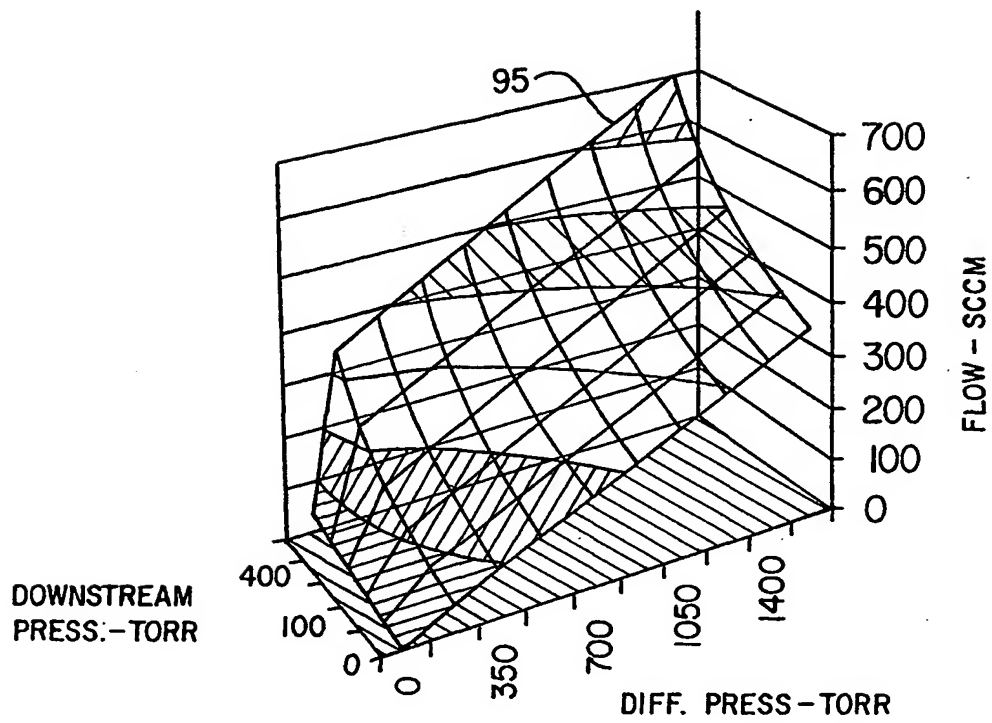below said measured temperature.
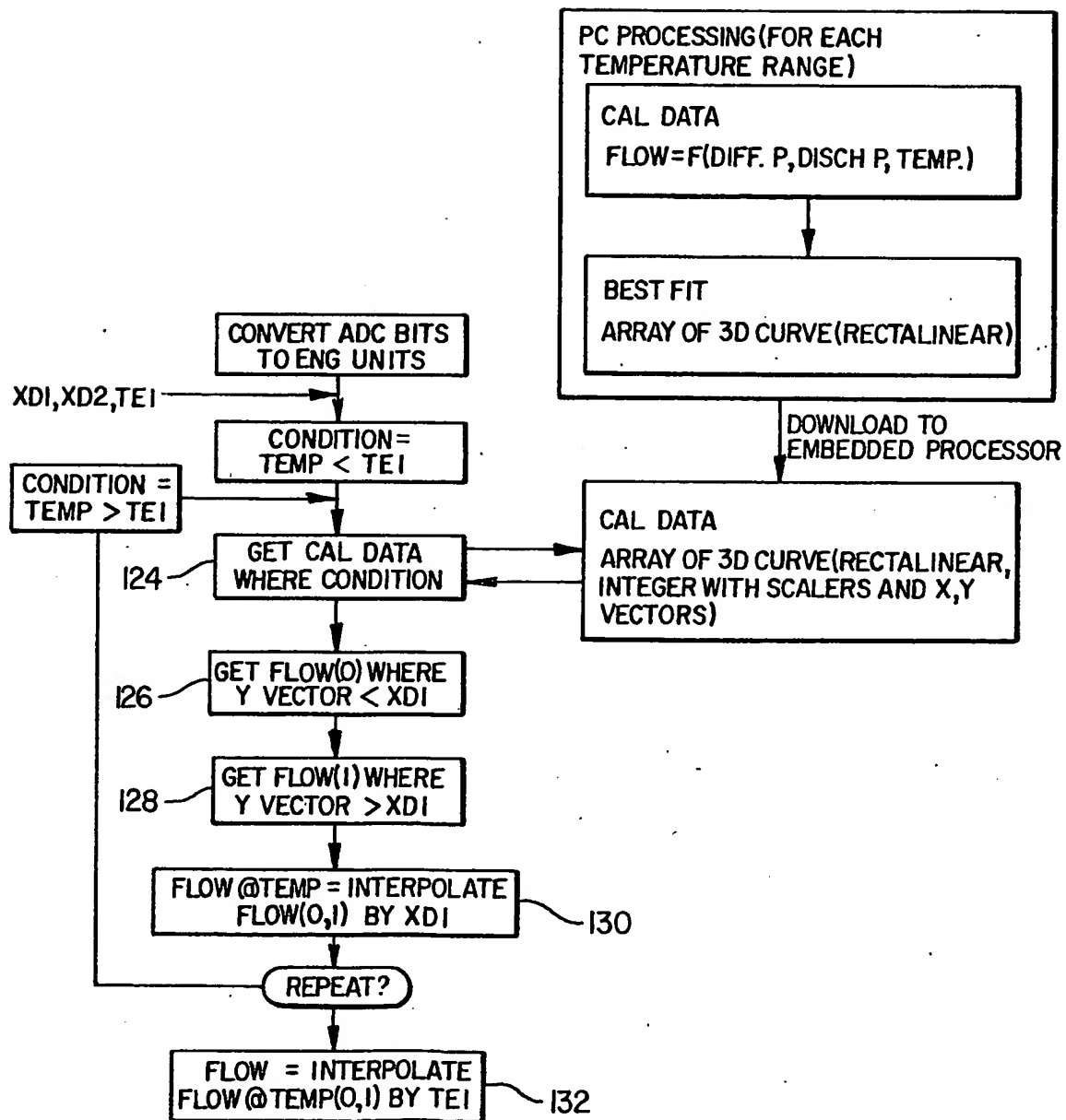
FIG. 1

FIG. 2

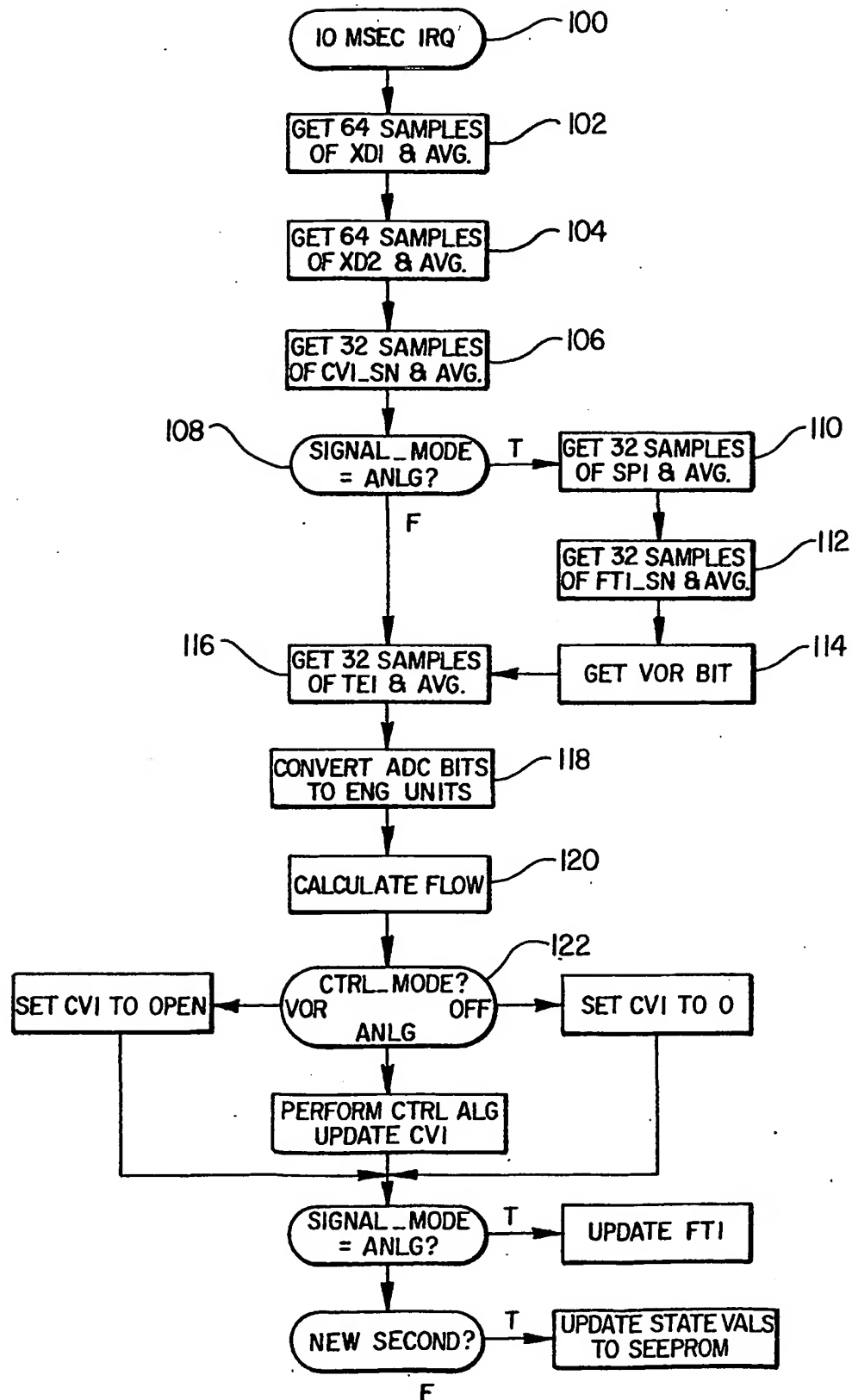**FIG. 3**

2/5

FIG. 4

FIG. 5

FIG. 6

4/5

FIG. 7A

5/5

PC PROCESSING (FOR EACH TEMPERATURE RANGE)

CAL DATA

FLOW = F(DIFF. P, DISCH P, TEMP.)

BEST FIT

ARRAY OF 3D CURVE (RECTALINEAR)

CONVERT ADC BITS TO ENG UNITS

XD1, XD2, TE1

CONDITION = TEMP < TE1

CONDITION = TEMP > TE1

124 — GET CAL DATA WHERE CONDITION

DOWNLOAD TO EMBEDDED PROCESSOR

CAL DATA

ARRAY OF 3D CURVE (RECTALINEAR, INTEGER WITH SCALERS AND X,Y VECTORS)

126 — GET FLOW(0) WHERE Y VECTOR < XD1

128 — GET FLOW(1) WHERE Y VECTOR > XD1

FLOW @ TEMP = INTERPOLATE FLOW(0,1) BY XD1 ~ 130

REPEAT?

FLOW = INTERPOLATE FLOW @ TEMP(0,1) BY TE1 ~ 132

FIG. 7B

INTERNATIONAL SEARCH REPORT

A.	CLASSIFICATION OF SUBJECT MATTER

IPC(7) :G05D 7/06; F16K 31/02
US CL   :137/487.5

According to International Patent Classification (IPC) or to both national classification and IPC

B.	FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. :   137/487.5, 486, 10; 138/44; 73/861.52

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C.	DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,868,159 A (LOAN et al.) 09 February 1999, see entire document.	1, 11, 15, 23, 24
Y		2 - 10, 12 - 14, 16 - 22, 25 -32
Y	US 4,796,651 A (GINN et al.) 10 January 1989, see entire document.	2 - 4, 12 - 14, 16 - 18, 25 -32
Y	Mott Industrial, Porous metal flow restrictors. June 1997, see entire document.	5 - 7, 19 - 22
Y	US 5,970,801 A (CIOBANU et al.) 26 October 1999, see entire document.	8 - 10

[X] Further documents are listed in the continuation of Box C.   [ ] See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 OCTOBER 2001	16 NOV 2001

| Name and mailing address of the ISA/US
Commissioner of Patents and Trademarks
Box PCT
Washington, D.C. 20231 | Authorized officer
MICHAEL P. BUIZ |
|---|---|
| Facsimile No.   (703) 305-3230 | Telephone No.   (703) 308 - 0871 |

Form PCT/ISA/210 (second sheet) (July 1998)*

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,406,161 A (LOCKE et al.) 27 September 1983, see entire document.	1 - 32